Reducing HFC Emissions for Bus Air Conditioning: A Change in Technology for Rooftop Applications

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Objective

Evaluate the potential reduction in HFC emissions for bus rooftop A/C systems by implementation of a new technology concept.

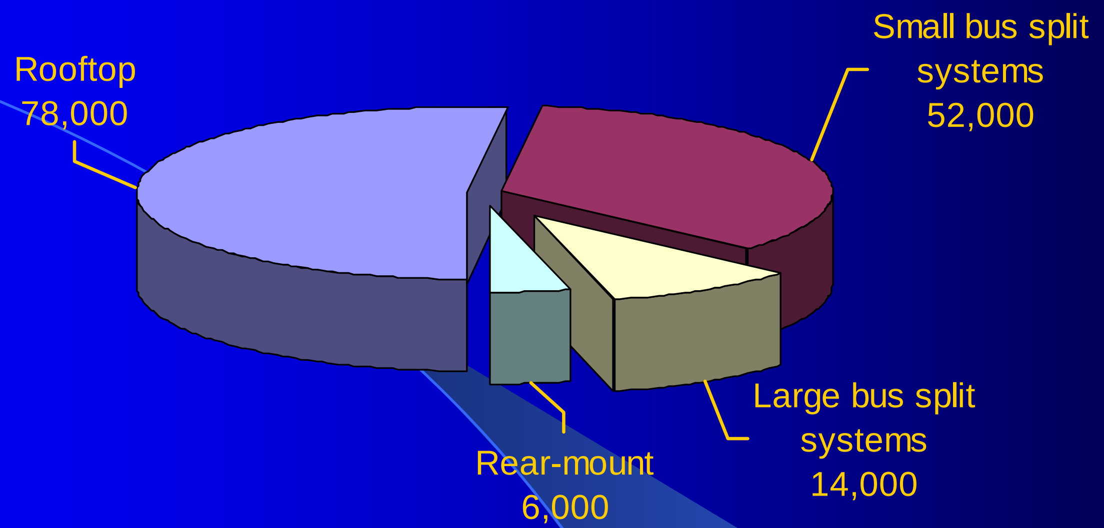
1. Assessment of present-day systems
   - Market overview
   - Review of baseline product technology
   - Estimation of HFC leak rates

2. Overview of new technology: Modular all-electric
   - Technology advancements
   - Estimation of HFC leak rates

3. Projected reduction in HFC emissions and associated Life Cycle Climate Performance.

Global Bus Air Conditioning Market

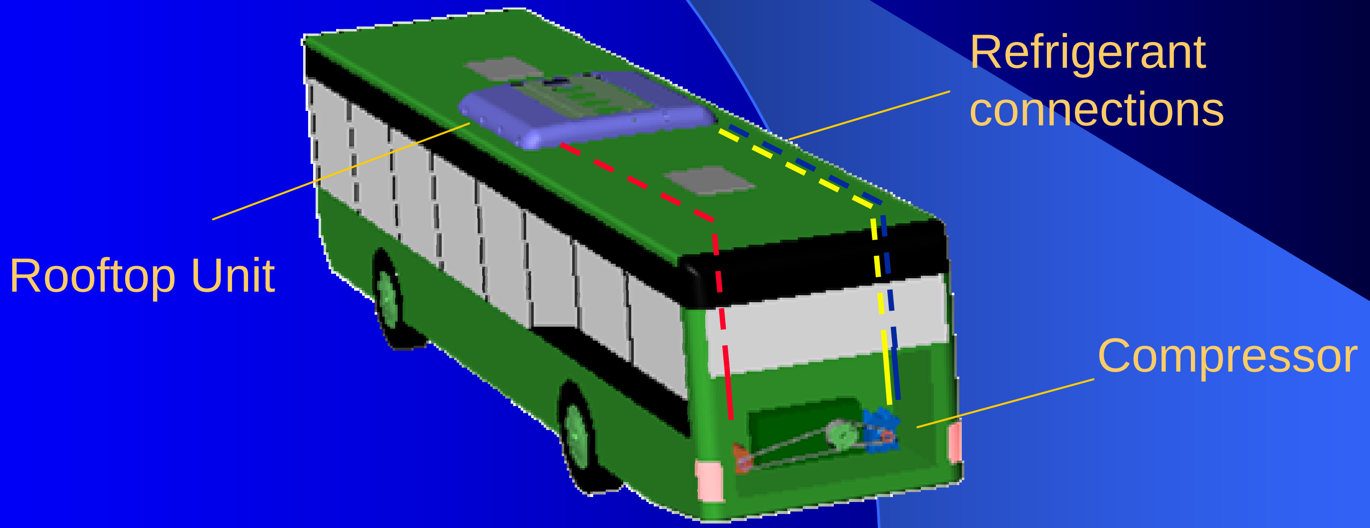
2003 (E) Bus A/C Market by Product Volume



- Approximately 150,000 units sold annually
- Considering only the large bus segment (bus length > 10m), rooftop applications represent 80% of the market.

Traditional Rooftop A/C Products

- Typical rated cooling capacity of 16, 24, or 32 kW, predominantly R-134a refrigerant.
- Utilize an open drive reciprocating compressor mounted in the engine compartment.
- Flexible refrigerant hoses connect rear mount compressor to rooftop unit.



Traditional Rooftop A/C Products

- R-134a has become the predominant refrigerant in the industry, and will be solely considered in this analysis.
- Analysis assumptions:
  - 24 kW nominal system cooling capacity
  - 6.0 kg R-134a system refrigerant charge
  - Suction / discharge line diameter of 22 / 16 mm
- HFC leak rates on current products are estimated by consideration of both industry reported data and calculated values.
- Given the wide range of reported data, leak rates are presented in two scenarios:
  - Scenario A: Leakage rate for a typical system
  - Scenario B: Leakage rate for the best case scenario

Industry Reported HFC Leak Rates

- Majority of system leaks caused by the following:
  - Refrigerant permeation through flexible hoses
  - Mechanical and/or brazed interconnecting joints
  - Compressor open-drive shaft seal
  - Loss during service / reclaim / recycling

- Estimated leak rates, not inclusive of end of life recycling losses, from industry studies:

System Type	Estimated Annual Leak Rate	Reference
Mobile (automotive)	10.5%	(3) (A.D. Little)
	9.2%	(4) (Baker)
	6.9%	(5) (Schwarz)
	18.5%	(6) (Petitjean)
	8.6%	(6) (Petitjean)
	Average = 10.7%	
Transport (bus)	"Up to 50%"	(7) (UNEP)
Packaged (hermetic)	3%	(3) (A.D. Little)

Flexible Hose Permeation Rates

- Allowable permeation rate (per SAE J2064) is 9.7 kg/m^2/yr. Hoses readily available on the market range from 9.0 – 2.4 kg/m^2/yr.

- Given the variation in hose quality selection and required lengths for each installation, the following two scenarios are considered:

Scenario A: "Typical Case"	**Scenario B: "Best Case"**
Hose permeation rate = 7.0 kg/m^2/yr Flex. hose length at each end = 1.25 m Suction/dischg. Size = 22/16 mm	Hose permeation rate = 2.4 kg/m^2/yr Flex. hose length at each end = 0.75 m Suction/dischg. Size = 22/16 mm

Piping and Mechanical Joints

- Typical systems have a combination of approximately 60 brazed and mechanical piping joints.
- Braze joints can be leak tested to a confidence level of 2.8 g/yr/joint, while mechanical joints are susceptible to deterioration over time.
- Given the difficulty in quantifying piping leak rates, the analysis utilizes industry data as a benchmark:

Scenario A: "Typical Case"	Scenario B: "Best Case"
Piping joint leak rates comparable to the automotive industry Leak rate = 10.7% / year	Piping joint leak rates comparable to hermetic packaged systems Leak rate = 3.0% / year

Compressor Shaft Seal

- Typical design target for compressor shaft seal leak rate is 12g/yr.
- Shaft seals are susceptible to deterioration over time, especially during extended periods of unit shutdown.
- Assumptions of leak rates are as follows:

Scenario A: "Typical Case"	Scenario B: "Best Case"
Compressor shaft seal leak rate 3x design target of 12g/yr	Compressor shaft seal leak rate maintained at target of 12g/yr

Servicing / End of Life Recycling

- Generally accepted service schedules for automotive A/C systems:
  - 12 year design life
  - (2) services/recharges over product life cycle (after 40% loss)
  - 6% loss during each refrigerant reclaim
  - 30% loss during end of product life recycling

- Due to the higher leak rates projected on bus systems, the service interval will be more frequent, and will vary for each system:

Scenario A: "Typical Case"	Scenario B: "Best Case"
Service frequency: Every 2 years Total services over product life: 6 Emissions during service: 6% x 6 Emissions from product recycling: 30%	Service frequency: Every 6 years Total services over product life: 2 Emissions during service: 6% x 2 Emissions from product recycling: 30%

Overview of New Technology

- Modular, all-electric approach to bus rooftop air conditioning
- Rear-mount, engine driven generator supplies electrical power to rooftop modules.
- Each module equipped with a hermetic rotary compressor, condenser, evaporator, and expansion device.
- Variable frequency inverter drives compressor and fan motors.
- Factory charged and brazed system.

Overview of New Technology

- Eliminates the need for the open drive compressor and flexible interconnecting lines.

- Each module designed for 8 kW nominal cooling capacity, with a design charge of 1.4 kg R-134a.

- In comparison to the baseline 24 kW traditional system, (3) modules would be utilized, yielding a 30% reduction in design refrigerant charge per application.

Estimation of Leak Rates

- The main sources of refrigerant leaks on the all-electric modular system are piping joints and service/recycling.
- Each modular air conditioning system is in essence a hermetic packaged system. The (3) module 24 kW system would have approximately 130 braze joints.
- The "Worst case" scenario assumes a 5% annual leak rate due to piping joints. This correlates to more than half of the joints leaking at the 2.8 g/yr leak check confidence level.
- The "Likely case" scenario assumes the system achieves the industry standard leak rate for packaged systems of 3% per year.

Estimation of Leak Rates

- The service frequency of the all-electric system is expected to be reduced significantly, due to the elimination of flexible refrigerant hoses, compressor shaft seal, and mechanical joints.

- "Worst case" and "Likely case" scenarios assume (2) and (1) services per unit life, respectively.

Comparison of HFC Leak Rates

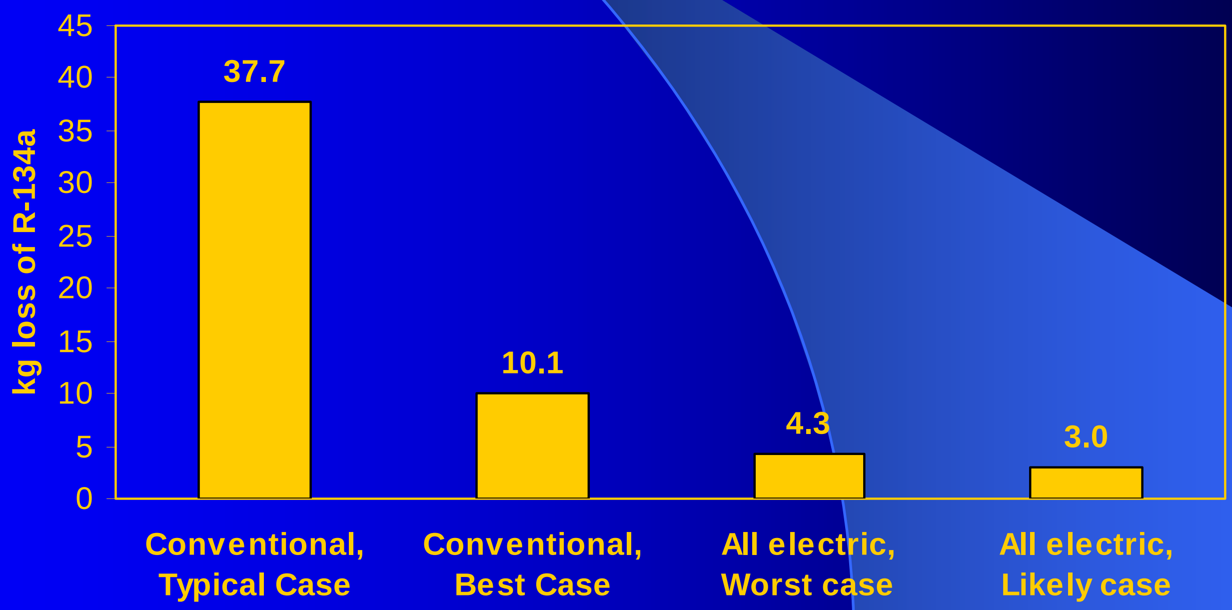
	CONVENTIONAL SYSTEM		MODULAR ALL-ELECTRIC	
	Scenario A Typical Case	**Scenario B Best Case**	**Scenario A Worst Case**	**Scenario B Likely Case**
Nominal system charge, kg R-134a	6.0	6.0	4.2	4.2
Flexible hoses				
Hose permeation rate, kg/m2/yr	7.0	2.4		
Flexible hose length @ each end, m	1.25	0.75		
Leak rate, kg/yr	**2.13**	**0.44**	**0**	**0**
Compressor shaft seal leaks, kg/yr	**0.04**	**0.01**	**0**	**0**
Braze leak rate	10.7% per year	3% per year	5% per year	3% per year
reference	Auto. Sys.	Packaged sys.	Exp. Joint leak rate	Packaged sys
Leak rate, kg/yr	**0.64**	**0.18**	**0.21**	**0.13**
Services per 12 year product life	6	2	2	1
6% loss during each service reclaim	2.16	0.72	0.50	0.25
Annual leak rate from service, kg/yr	**0.18**	**0.06**	**0.04**	**0.02**
30% loss at end-of-life product recycle	**1.80**	**1.80**	**1.26**	**1.26**
Total emission before recycling, kg/yr	**2.99**	**0.69**	**0.25**	**0.15**
Annual leak rate excluding recycling	**49.8%**	**11.5%**	**6.0%**	**3.5%**
Total emission including recycling, kg/yr	**3.14**	**0.84**	**0.36**	**0.25**
Annual leak rate including recycling	**52.3%**	**14.0%**	**8.5%**	**6.0%**

Comparison of HFC Leak Rates

- **Up to a ten fold reduction in HFC emissions is possible**

	Annual Leak Rate	Annual R-134a Loss per 24 kW system
Conventional	14.0 - 52.3 %	0.84 - 3.14 kg
All-Electric	6.0 - 8.5 %	0.25 - 0.36 kg

R-134a Emissions over 12 Year Product Life



Life Cycle Climate Performance

- The analysis was limited to LCCP parameters related specifically to HFC emissions:

Direct Contributions

- Leaks during product manufacture
- Leaks during product operation & servicing
- Emission during end-of-life product recycling

Indirect Contributions

- Energy required to produce product materials (refrigerant only)

GWP of R-134a = 1300 (100 year integrated time horizon)

Equivalent CO_2 Emissions Comparison

Equivalent CO_2 Annual Emissions per 24 kW System

	Direct Contribution Equiv. Annual Emission kg CO_2	Indirect Contribution Equiv. Annual Emission kg CO_2	Total Equiv. Annual Emission kg CO_2
Conventional			
Scenario A: Typical Case	4,069	78	4,147
Scenario B: Best Case	1,092	"	1,170
All Electric			
Scenario A: Worst Case	468	55	523
Scenario B: Likely Case	325	"	380

- **An all-electric bus AC system shows a potential reduction in eq. CO_2 emissions of 647 – 3767 kg per bus, per year.**
- **Considering the avg. automobile LCCP of 3300 (275 kg eq. CO_2/yr), the reduction potential on each bus system represents 2-13 equivalent automobiles.**

Conclusions

- Annual leak rates of conventional bus rooftop A/C systems were estimated to be 14.0 – 52.3 %.

- All-electric systems were shown to have potential annual leak rates of 6.0 – 8.5%, along with a 30% reduction in system design refrigerant charge.

- All-electric systems will enable up to a ten fold reduction in HFC emissions (38 kg down to 3 kg) over the entire product lifecycle.

- The resulting reduction in equivalent CO_2 emissions is estimated to be 55 – 91% for all-electric systems.

Q & A